



Engineering Bulletin

Separation/Concentration Technology Alternatives for the Remediation of Pesticide-Contaminated Soil

Purpose

Section 121(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), mandates the U.S. Environmental Protection Agency (EPA) to select remedies that "utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practical" and to prefer remedial actions in which treatment "permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances, pollutants, and contaminants as a principal element." The Engineering Bulletins are a series of documents that summarize the latest information available on selected treatment and site remediation technologies and related issues. They provide summaries of and references for the latest information to help remedial project managers, on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to evaluate a technology or technologies for potential applicability to their Superfund or other hazardous waste site. Those documents that describe individual treatment technologies focus on remedial investigation scoping needs. Addenda will be issued periodically to update the original bulletins.

Abstract

Pesticide contamination includes a wide variety of compounds and may result from manufacturing improper storage, handling, disposal; or agricultural processes. It can occur in soil and can lead to secondary contamination of groundwater. Remediation of pesticide-contaminated soils can be a complicated process, as most pesticides are mixtures of different compounds rather than pure pesticide. The remedial manager is faced with the task of selecting remedial options that will meet established cleanup levels. There are three principal options for dealing with pesticide contamination: containment/immobilization, destruction, and separation/concentration. This bulletin focuses on soils and current or soon-to-be available separation/concentration pesticide remediation technologies. The information presented is condensed from the technical resource document "Contaminants and Remedial Options at Pesticide Sites" [1] and other available literature. Technologies that

have not produced performance data are not included nor are water, sludge, or sediment treatment technologies. The resource document contains site-specific information on pesticide contamination and the remediation techniques used.

Background

Pesticides, as defined by the U.S. Federal Environmental Pesticide Control Act, are "...any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any insect, rodent, nematode, fungus, weed or any other form of terrestrial or aquatic plant, animal life, or virus, bacteria or other microorganism which the Administrator declares a pest" [2]. Pesticides include insecticides, fungicides, herbicides, acaricides, nematocides and rodenticides as well as any substance or mixture of substances intended for use as a plant regulator, defoliant or desiccant. Pesticides do not include such substances as fertilizers or veterinary medicines [1]. The EPA has developed extensive data on specific pesticide products and wastes through the pesticide registration program and site investigation [3,4,5].

Pesticide wastes are generally complex chemical mixtures and not pure pesticides. These mixtures can include solvents, carriers and other components that will have a direct effect on toxicity, mobility, transport and treatment.

The resource document categorizes pesticides into four waste groups based on available treatment technologies [1]. The four waste group categories are:

- WG01 - Inorganic pesticides
- WG02 - Halogenated water insoluble organics
- WG03 - Halogenated sparingly water soluble organics and organo-linked compounds
- WG04 - Nonhalogenated organics and organo-linked compounds.

Table 1 details the four pesticide waste groups and gives examples of commonly found pesticides. These groups are subdivided further to show the chemical class or

[] indicate references



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Table 1. Pesticide Chemical Waste Groups.* [1,6]

Pesticide Chemical Waste Group	Family	Example	Applicable Soil Treatment Technologies
WG01 – Inorganics		Lead arsenate Sodium fluoride Zinc phosphide	Chemical oxidation Soil flushing Stabilization/Solidification Soil washing
WG02 – Halogenated water insoluble organics	Organochlorine/ DDT analog	DDD DDE DDT	Incineration Bioremediation Dehalogenation/Hydrodehalogenation
	DDT analog	Methoxychlor	Hydrolysis/Neutralization
	Cyclodiene	Aldrin Chlordane Dieldrin Endosulfan Endrine Heptachlor	Ultra high temperature processes Soil flushing Soil washing Thermal desorption Steam extraction Solvent extraction Supercritical CO₂ extraction
	Hexachlorocyclohexane	α - BHC β - BHC γ - BHC (lindane)	Adsorption Filtration
	Toxaphene	Toxaphene	Chemical reduction
	Nitrated aromatics	Pentachloro-nitrobenzene	Chemical oxidation Radio frequency heating
	Nitrated aliphatics	Chloropicrin	
	Alkylmercaptan	Captan	
	Carboxamide	Alachlor Pronamide	
	Triazine	Cyanazine	
WG03 – Halogenated sparingly water soluble organics and organo-linked compounds	Halogenated phenol	Pentachlorophenol (PCP)	Incineration Bioremediation Dehalogenation/Hydrodehalogenation
	Halogenated volatile aliphatics	Dibromochloropropane (DBCP) Ethylene dibromide (EDB) Methyl bromide	Hydrolysis/Neutralization Ultra high temperature processes Soil flushing Soil washing Soil vapor extraction
	Aryloxyalkanoic acid	2,4-D 2,4,5-TP (silvex)	Thermal desorption Steam extraction
	Phosphorothioate	Methyl parathion	Solvent extraction
	Dinitroaniline	Trifluralin	Supercritical CO₂ extraction Chemical oxidation Adsorption Filtration Chemical reduction Radio frequency heating
WG04 – Nonhalogenated organics and organo-linked compounds	Unsaturated aliphatics	Acrolein	Incineration Bioremediation Hydrolysis/Neutralization
	Thiourea	Ethylene oxide Ethylene thiourea (ETU)	Ultra high temperature processes Soil flushing
	Alkaloids	Allethrin Rotenone	Soil washing Thermal desorption
	Carbamates	Aldicarb Benomyl Carbaryl	Steam extraction Solvent extraction Supercritical CO₂ extraction
	Phosphonates	Diazinon Glyphosate	Chemical oxidation Adsorption
	Phosphorothioates	Dimethoate Marathon Parathion Phorate	Filtration Chemical reduction

*The Bulletin covers only the technologies in **bold**. Discussions on the other technologies can be found in the resource document.

family each pesticide belongs to according to their molecular structure or key functional group. Applicable treatment technologies for each waste group are also provided. References to pesticides and pesticide wastes in this document use the above waste group categories.

Most pesticides readily adsorb on soils because of their high adsorption capacity. In fact, adsorption of pesticides on the soil surface is a dominant factor that affects the extent of the site contamination. As a rule, when applied properly, pesticides migrate slowly. Concentrated pesticide from a spill or leak, however, can move more quickly into the subsurface, especially if the pesticide is in aqueous phase or under the influence of percolating water [1]. Mechanisms of pesticide fate and transport that affect the extent of site contamination include:

- Adsorption on soils
- Biodegradation
- Volatilization
- Downward migration
- Lateral migration
- Photolysis.

Selecting a remedial strategy includes considering the individual contaminant's toxicity, persistence, migration pathways and rate of transport from a site. The wide range of physical and chemical properties of pesticides also influence the selection of an appropriate remedial technology or combination of technologies (known as a treatment train). It is important to gain information specific to the pesticide(s) present in order to effectively identify the treatment technology(ies) that is most applicable and cost effective.

Separation/Concentration Options

Treatment technologies or control options for pesticides fall into three categories: containment/immobilization, destruction and separation/concentration. This document addresses the separation/concentration options.

Separation/concentration technologies primarily serve to separate contaminants from soils, thereby concentrating the waste stream and reducing the amount of material that must be treated. These technologies are mainly used as a pretreatment step, since no destruction or reduction of toxicity is attained.

Separation/concentration technologies can be classified as follows:

- *In situ* technologies
 - Soil flushing
 - Soil vapor extraction (SVE)
 - Steam extraction
 - Radio frequency (RF) heating
- *Ex situ* technologies (excavated soils)
 - Thermal desorption
 - Soil washing
 - Solvent extraction
 - Supercritical CO₂ extraction.

The decision to select and implement these techniques rests primarily on the action levels established for the site. Key issues for these technologies are the management, treatment and disposal options for the process extract phase. While not discussed in this bulletin, regulatory compliance and disposal criteria for extract-phase materials must be addressed.

Separation/concentration technologies can potentially be applied to pesticide wastes in all four waste groups. Soil flushing, SVE and steam extraction technologies have limited applicability to pesticide-contaminated soils, thus these separation/concentration technologies are not discussed in this document. In this bulletin, the following separation/concentration technologies most applicable to pesticide-contaminated soils are discussed:

- Radio frequency heating
- Thermal desorption
- Soil washing
- Solvent extraction
- Supercritical carbon dioxide (CO₂) extraction.

For each separation/concentration option presented, the following items are discussed:

- Process description
- Data needs for technology implementation
- Technology performance in treating pesticides in soils
- Process residuals (if available)
- Site-specific regulatory requirements or goals (if available).

Radio Frequency Heating

Radio frequency (RF) heating is an *in situ* soil treatment process that uses electromagnetic energy in the radio frequency band to heat soil rapidly. During this process, the contaminants are vaporized and/or boiled out along with water vapor formed by the boiling action of native soil moisture. The gases and vapors formed upon heating the soil are recovered and treated on site. This combination of vaporization, boiling, and steam stripping has been used effectively in removing aldrin, dieldrin, endrin, isodrin (WG02) and other pesticides that typically volatilize in the temperature range of 80°C to 300°C, such as volatile aliphatics (WG03). This technology offers three distinct advantages:

- the contaminated materials do not need to be excavated;
- the contaminants are removed from the soil as vapors and can be subsequently trapped and treated in a vapor treatment system (process equipment may be trailer mounted and mobile);
- the presence of other contaminants such as jet fuel, polychlorinated biphenyls (PCBs), creosote, petroleum hydrocarbons, does not limit the treatment effectiveness of the process [7,8,9].

Process Description

The RF soil decontamination process heats a defined volume of soil *in situ* to temperatures of 80°C to 300°C by

means of an electrode array inserted in bore holes drilled into the soil. The process uses electromagnetic energy in the frequency range of 2 to 13 megahertz to achieve high soil temperatures. The actual frequency depends upon the volume and depth of the treated soil and the dielectric properties of the soil.

The electrodes, spaced evenly apart in the soil, are 2 to 15 ft long. The soil between the electrodes is heated by the RF energy during treatment. Some of the electrodes are perforated to serve as vapor collection lines which are manifolded to a vapor treatment system [7,8,9].

Data Needs for Technology Implementation

The data needs for RF heating are presented in Table 2.

Performance

A field pilot demonstration of this technology was conducted at the Rocky Mountain Arsenal. The pesticide-contaminated soil was a mixture of clay and sand to a depth of 12 feet and gravelly sand to a 17-ft depth. The results are summarized in Table 3. The initial concentrations shown are the average of 36 samples at depths of 7 to 17 ft. The final contaminant concentrations shown are averages in the 200-250°C, 250-300°C, and >300°C temperature ranges. The contaminant removal percentage was greater than 98 percent.

The preliminary cleanup goals, set by EPA and state agencies, were developed on a risk-based assessment of 10⁻⁶ biological worker exposure. Table 4 shows the final pesticide concentrations in treated soil for each of the three treatment temperature ranges, with the associated cleanup goal for each pesticide. The data indicate that the best

Table 2. Data Needs for Radio Frequency Heating. [7,8]

Data Needs	Possible Effects
Type of soil	Low permeability soils increase costs and decrease contaminant recovery; dielectric properties of soil determine RF power requirement
Presence of metal drums or metallic debris	Disrupts current flow; may interfere with electrode placement
Type of contaminants(s)	Requires supplementation with other treatment methods if nonvolatile contaminants (boiling points >300°C), heavy metals, or inorganic salts are present
Soil moisture content	High moisture content increases energy requirements and impacts removal efficiency of organic contaminants
Flow rate and depth of groundwater table	Presence of fast moving groundwater in heated zone acts as an energy sink and negatively impacts process cost; may require diversion of water from heated zone by slurry walls, etc.

Table 3. Results of Radio Frequency Heating Pilot Test Program at Rocky Mountain Arsenal Over All Temperature Ranges Tested^a. [7]

Pesticide	Initial Concentration (ppm)	Final Concentration (ppm)	Percent Removal
Aldrin	1100	11.3	99.0
Dieldrin	490	3.2	99.3
Endrin	630	2.8	99.6
Isodrin	2000	33	98.4

^a200-250°C, 250-300°C, and >300°C

Table 4. Final Concentrations of Compounds versus Soil Temperature in Radio Frequency Test at Rocky Mountain Arsenal [9].

Pesticide	200-250°C Concentration (mg/kg)	250-300°C Concentration (mg/kg)	>300°C Concentration (mg/kg)	Preliminary Remediation Goal (mg/kg)
Aldrin	0.97 (±1.0) ^a	31 (±40)	1.8 (±3.1)	0.56
Dieldrin	0.59 (±0.35)	8.0 (±8.0)	1.0 (±1.5)	0.40
Endrin	1.7 (±2.0)	5.6 (±5.3)	1.1 (±1.5)	17
Isodrin	1.3 (NA) ^b	48 (±62)	49 (±90)	3.6

^aValues in parentheses represent the standard deviation of the concentration given

^bNA = Not available

overall treatment was achieved in soils heated to between 200 and 250°C. In this temperature range removal of both endrin and isodrin met the cleanup criteria [9].

Process Residuals

The vapors and gases collected by the second step of the process require treatment, combustion and/or scrubbing to remove acid gases. The condensed liquids from the collection phase are separated into aqueous and organic fractions. The aqueous phase is treated using activated carbon and filtration. The organic phase is collected for destruction at an approved facility [7,8,9].

Thermal Desorption

Thermal desorption is an innovative *ex situ* technology which includes a broad range of processes using thermal energy (e.g., heated air, infrared volatilization, laser-induced desorption, etc.) to remove volatile and semivolatile organic and inorganic compounds from contaminated soil.

Thermal desorption is applicable to pesticide waste from waste groups WG02, WG03, and WG04. Toxicity is not affected by thermal desorption; the toxic compounds are removed from the soil for further treatment or disposal [1].

Process Description

Thermal desorption is used to desorb low, medium and high boiling-point organic pesticides. Front-end material handling steps such as excavation, dewatering and/or dredging are performed. High soil moisture content may require greater energy usage, but it may also enhance volatilization

by producing steam within the media. The desorption units typically require at least 20 to 30 percent solids by weight. Some units can accept only 10 percent total organic carbon loading by weight.

The media enters the desorber unit and is heated to temperatures between 95 and 540°C. A temperature above 150°C may be required to effectively desorb medium-to-high boiling point organic pesticides. The vapors generated from the process can be destroyed/oxidized in an afterburner. The afterburners operate in excess of 870°C and have a fluid residence time sufficient to achieve a destruction efficiency greater than 99.99 percent.

The efficiency of thermal desorption is primarily dependent on the bed temperature and residence time in the unit. Residence time determines the soil treatment temperature for a given airflow rate. The resulting air and soil temperatures affect the rate and degree of contaminant desorption. A temperature differential of approximately 95°C higher than the boiling point of a pesticide is required to achieve complete desorption and to overcome the intrinsic heat transfer resistances present in the medium [1,11].

Data Needs for Technology Implementation

The data needs are presented in Table 5.

Performance

Thermal desorption technology has been used in several remedial actions including three Superfund sites. The Low Temperature Thermal Aeration (LTTA) System is a

Table 5. Data Needs for Thermal Desorption. [12,13,14]

Data Needs	Possible Effects
Moisture content	High moisture content (>20%) increases energy requirement; dewatering or pretreatment may be required
Particle size distribution	Oversize (>1-1.5 in.) particles may require size reduction or screening; presence of fine silt or clay may generate fugitive dust loading for air pollution control equipment
Total solids content	Usually a minimum of 20-30% solids is required
pH	Very high (>11) or low (<5) soil pH may result in corrosion of system components
Contaminant concentrations	Total organic bonding is limited to approximately 10%; higher organic bonding may result in incomplete processing
Presence of metals or inorganics	Are not likely to be treated effectively
Volatile metals	May concentrate in off-gas and require additional treatment
Total chlorine	May affect volatilization of some metals
Total petroleum hydrocarbons	High concentrations may require a thermal oxidizer or afterburner and a quench tower for cooling
Vapor pressure	Affects removal effectiveness; high contaminant vapor pressure increases removal efficiency and requires less energy for contaminant removal
Boiling point	Affects process temperature and removal effectiveness; low boiling point reduces energy requirements for contaminant removal
Adsorptive properties of contaminant	Affects amount of energy required to desorb contaminant from soil particles

remedial system developed by Canonie Environmental Services Corporation. The LTTA System thermally desorbs organic compounds from contaminated soil without heating the soil to combustion temperatures. The system performs three main operations: soil treatment, emissions control and process water treatment. LTTA systems can treat a wide variety of soils having different moisture and contaminant concentrations, and can remove pesticides from soil to below or near analytical detection limits [11].

The LTTA System was used in a full-scale Superfund Innovative Technology Evaluation (SITE) demonstration conducted at an abandoned pesticide mixing facility in western Arizona. The facility stored and mixed several pesticides including toxaphene, DDT, DDD, and DDE. The Arizona pesticide site was remediated under supervision of the state by voluntary action of the potentially responsible party. All treated soils at the site were required to contain

less than 5 mg/kg total pesticide after one pass through the LTTA system, as stated in the remedial action plan. An estimated 51,000 tons of contaminated soil required treatment. Sliding scale cleanup criteria were established, shown in Table 6, with a maximum allowable concentration of 1.09 mg/kg of toxaphene with no DDT/DDD/DDE (combined) at one end, and a maximum allowable concentration of 3.53 mg/kg DDT/DDD/DDE with no toxaphene at the other end. Treated soils met the specific cleanup criteria if 90 percent of the treated soil fell within the cleanup criteria on a daily basis.

The LTTA SITE demonstration consisted of three separate runs, each requiring about 8 hr to complete. Based on site characterization data of the contaminant distribution, the soil was treated to a depth of 2 ft. This soil was primarily clay-like in nature (40 percent fines).

Table 6. Sliding Scale Cleanup Criteria Concentrations for Pesticides During the LTTA™ SITE Demonstration of Thermal Desorption [14].

DDT/DDD/DDE (mg/kg)	0.00	0.01	0.83	1.00	2.00	3.00	3.36	3.52
Toxaphene (mg/kg)	1.09	1.087	0.83	0.78	0.47	0.16	0.05	0.00

Table 7. Pesticide Concentrations and Removal Efficiencies in LTTA™ SITE Demonstration of Thermal Desorption Technology. [14]

Pesticide	Conc. Range in Feed Soil, mg/kg	Average ^a Concentration, mg/kg						Removal, %		
		Run 1		Run 2		Run 3		Run 1	Run 2	Run 3
		Feed Soil	Treated Soil	Feed Soil	Treated Soil	Feed Soil	Treated Soil			
Toxaphene	4.5 to 47	27.5	<0.017	16.5	0.017	10.8	<0.025	>99.9	>99.9	>99.8
DDT	1.2 to 54	24.1	<0.001	22.8	0.001	9.3	0.002	>99.9	99.9	99.9
DDD	0.027 to 0.86	0.34	<0.0003	0.12	<0.0003	0.2	<0.001	>99.9	>99.7	>99.8
DDE	3.7 to 15	7.1	1.1	8.3	0.97	5.1	0.28	90.2	88.4	93.3

^aAverage of four composite samples for each feed or treated soil value

Demonstration results, shown in Table 7, indicate toxaphene, DDT, DDD, and DDE removals in excess of 99 percent for each of the three runs. The remedial cleanup criteria were met during each of the runs [11,14].

Williams Environmental Services (WILLIAMS) completed a treatability study using the WILLIAMS thermal desorption system for a removal action at a former pesticide formulation site (T H Agriculture and Nutrition Company) in Albany, GA. The removal action, which included treatment of approximately 3,000 tons of soil contaminated with over 1,000 mg/kg total pesticides, was overseen by EPA and the Georgia Department of Natural Resources Environmental Protection Division. Treatability study results showed that at a soil treatment temperature of 500°F, total pesticide

removal ranged from 86 to 93 percent; when operated at a treatment temperature of 700°F, pesticide removal was more than 99 percent. At 700°F, the total pesticide concentration was reduced from about 200 mg/kg to less than 0.003 mg/kg [15].

Process Residuals

This innovative technology produces the following three residual streams:

- Decontaminated soil, sludge or sediment
- Scrubber water from the air pollution control system
- Off-gas emissions from the air pollution control system [1].

The decontaminated media may be reclaimed after analysis. The scrubber water can be treated onsite or discharged to a publicly-owned treatment works (POTW). Off-gas emissions may require additional air pollution control before being released through a stack [1].

Soil Washing

Soil washing is an innovative *ex situ* technology which uses an aqueous solution to decontaminate soils. Contaminant removal or volume reduction is achieved by one or more of the following mechanisms: 1) the contaminants are suspended or dissolved in the wash solution, 2) the contaminants are concentrated by segregating the most contaminated fraction from the bulk of the soil using size-separation techniques or 3) the contaminants are concentrated by segregating dense, particulate contaminants through the use of density-separation techniques [16,17,18,19,20,21]. Each of the four pesticide chemical waste groups (Table 1) can potentially be treated using the soil washing technology [1].

Process Description

Soil washing systems consist of specific unit operations (subsystems) that are tailored to accommodate the site conditions and soil characteristics. In general, soil washing systems consist of three types of subsystems:

- feedstock preparation
- soil washing
- residuals treatment.

Feedstock preparation includes excavation, transportation of the soil to the soil-washing staging area, removal of debris and separation of the soil into different particle-size or density fractions. Typical post-excavation operations

include screening, crushing and attrition scrubbing. The purpose of feedstock preparation is to segregate the soil components into fractions based on contamination levels. Minimally contaminated soils, requiring little or no treatment, can be returned to the site as backfill, but highly contaminated fractions require more aggressive treatment. Reducing the volume of soil passing through the remainder of the system increases the cost-effectiveness of the technology [16,17,18,19,20,21].

Soil washing unit operations tend to fall into two categories: physical separation of the soil matrix into different particle-size or density fractions, and chemical separation of the contaminants from the soil matrix. Organic contaminants such as pesticides are often concentrated in the fines (e.g., clays and silt). Physical separation of this fraction using unit operations such as flotation, gravity settling, hydrocloning, washing and rinsing achieves further volume reduction [16,17,18,19,20,21]. Chemical separation transfers the contaminant from the soil matrix to the aqueous-phase wash solution. Chemical separation can be enhanced by optimizing process conditions. Increased wash or rinse temperature, addition of surfactant and pH adjustment may enhance pesticide removal [16,17,18,19,20,21].

Residuals treatment subsystems include unit operations that treat process water, air emissions and highly contaminated fractions of the soil, such as the fines. The unit operations typically include biological, chemical or thermal oxidation units for destruction of residual contamination, as well as adsorption processes to further concentrate the contaminants.

Data Needs for Technology Implementation

Data needs for soil washing are presented in Table 8.

Table 8. Data Needs for Soil Washing. [21,22]

Data Needs	Possible Effects
Particle size distribution	Affects efficiency of removal from wash liquid; particles >2 inches in diameter require pretreatment for oversized particles; particles <0.063 mm in diameter are difficult to wash
Soil type	Affects pretreatment and transfer requirements; high clay and silt levels make it difficult to remove contaminants because of their strong adsorption to the particles
Complex waste mixtures	Increases difficulty in formulating suitable washing fluid; solubility of different contaminants may vary
Wash solution	Presence of surfactants or other reagents in wash solution may cause difficulties in wastewater and sludge treatment/disposal
Metal content	Concentrations and species affect selection of wash fluid, mobility of metals, and post-treatment
Organic content	Concentration and species affect selection of wash fluid, contaminant mobility and post-treatment
Partition coefficient (K_{OW})	High coefficient requires excessive volumes of wash fluid since contaminant is tightly bound
pH, buffering capacity	Can affect pretreatment requirements, wash fluid selection, and choice of materials of construction for equipment

Performance

Soil washing is an innovative technology available for full-scale implementation. It has been used as a remediation technology at several Superfund sites [23]. A pilot-scale soil-washing treatability study was conducted on pesticide-contaminated soil at the Sand Creek Superfund site in Commerce City, CO. The treatability study consisted of 23 individual runs conducted under varying process conditions. The process variables tested included:

- depth of soil excavation
- surfactant type and concentration
- wash water temperature

- pH
- number of washes
- liquid-to-solids ratio.

Table 9 provides a summary of the treatability study results. Experimental conditions and results of the individual runs are shown in Table 10.

Control runs using only ambient-temperature municipal water without surfactants addition demonstrated removal of 76 to 81 percent dieldrin and 67 to 81 percent heptachlor from the coarse soil fraction. Results indicate that surfactant addition had a positive influence on pesticide removal [24,25].

Table 9. Summary of Sand Creek Superfund Site Soil Washing Treatability Study Results [24].

Soil Fraction	Concentration (mg/kg)		Removal (%)	
	Dieldrin	Heptachlor	Dieldrin	Heptachlor
Feed	2.7 to 27	8 to 460	NA ^a	NA
Treated Coarse	0.0 to 6.8	1.4 to 50	-44 to 91	17 to 99
Treated Fines	0.0 to 37	4.4 to 340	-131 to 86	-100 to 97

^aNA = Not applicable

Table 10. Sand Creek Superfund Site Soil Washing Treatability Study Results [24].

Run #	Surfactant (%)	Test Conditions				Heptachlor (mg/kg)		Dieldrin (mg/kg)	
		Temp. (°F)	pH	Soil Depth (feet)	Liq./ Soil Ratio	Feed Soil	Treated Soil	Feed Soil	Treated Soil
1	none	ambient	7	0-1	6:1	220	50	19	4.6
2	none	130	10	0-1	6:1	87	29	16	2.4
11	none	130	10	0-1	(9:1)	150	37	24	4.5
12	none	130	7	0-1	6:1	170	34	23	4.5
6	0.4A	130	10	0-1	6:1	180	26	17	6.8
7	1.0A	130	10	0-1	6:1	230	25	18	2.9
23	1.0A	130	10	0-1	6:1	230	15	18	5.6
3	0.4S	130	10	0-1	6:1	100	24	19	2.0
8	1.0S	130	10	0-1	6:1	200	36	17	4.4
9	1.0S	130	10	0-1	6:1	270	28	27	3.9
10	0.4S	130	10	0-1	6:1	260	34	25	4.9
17	0.4S	130	10	0-1	6:1	22	12	2.8	1.5
4	0.4T	130	10	0-1	6:1	220	27	18	5.0
5	0.5T	130	10	0-1	6:1	220	30	20	5.0
18	1.0T	130	10	0-1	6:1	120	16	13	1.7
18A	1.0T	130	10	0-1	6:1	120	18	16	1.8
19	1.5T	130	10	0-1	6:1	250	16	18	3.2
19A	1.5T	130	10	0-1	6:1	250	20	18	2.0
20	1.0T	130	10	0-1	(9:1)	64	12	19	1.9
20A	1.0T	130	10	0-1	(9:1)	64	14	19	1.6
21	1.0M	130	7	0-1	6:1	460	16	20	2.6
22	1.0M	130	10	0-1	6:1	210	22	17	3.8
13	1.0S	130	10	1-3	6:1	63	19	9.7	1.9
14	1.0T	130	10	1-3	6:1	120	1.8	17	2.2
15	1.0T	130	10	0-5	6:1	8	2.0	2.7	<1.6
16	1.0S	130	10	0-5	6:1	12	<1.6	3.4	<1.6

A = Adsee; S = SDS; T = Tergitol; M = SDS/Tergitol mix

The site cleanup criteria, established in the Record of Decision (ROD) by EPA Region VIII, were 0.55 mg/kg for heptachlor and 0.15 mg/kg for dieldrin. The analytical detection limits, 1.6 mg/kg for both contaminants, were not low enough to determine if these action levels were met [25]. This was due to matrix interferences.

Bench-scale soil-washing tests conducted at the FMC Fresno Superfund site demonstrated that contaminant reduction for any size fraction greater than 200 mesh is most influenced by the number and types of washes used. A single wash removed about 77 percent of the dieldrin from soil, but three washes using a surfactant removed 99 percent [26]. Additional studies at the FMC site were performed using a froth flotation wash. Data indicate that this surfactant-assisted wash procedure removed an average of 80 to 85 percent of the organochloropesticides (WG02 and WG03) in one wash cycle; 92 to 99 percent removal was achieved with a triple wash. Froth flotation washing removed 81 to 85 percent of the organo-phosphorus pesticides with one wash cycle [26].

High percentages of clay, silt, and humic content may have a negative effect on contaminant removal and overall volume reduction. This is because pesticides bind chemically or physically more readily to clay and silt particles. Media with high cation exchange capacity also bind some organic and organo-metallic pesticides that may be difficult to separate using this technology [17,27,28].

Process Residuals

Residuals from the aforementioned process units may include oversize rocks, debris, and coarse material, air emissions, wastewater, and contaminated sludges or fines. Oversize fractions are often minimally contaminated and can be returned as backfill to the site with little or no treatment. Debris that is porous in nature, such as wood, roots, and vegetation, may be highly contaminated and require off-site disposal. Treatment units for pesticide-laden system wastewater include carbon adsorption, chemical or photochemical oxidation, or biological oxidation. Contaminated fines resulting from the soil washing subsystem can be treated either on or off site by processes such as biological or chemical oxidation, incineration or solidification/stabilization in conjunction with land disposal [16,17,18,19,20,21].

Solvent Extraction

Solvent extraction is an innovative technology that uses organic solvents to extract organic contaminants from soils. Solvent extraction is mainly applicable to the decontamination of soils containing volatile and nonvolatile hydrophobic organics, such as pesticides. This technology achieves volume reduction by concentrating the pesticides into an extract phase, from which the contaminants can be recovered, further concentrated or disposed.

There are two broad categories of processes: conventional solvent extraction and supercritical fluid extraction. Conventional solvent extraction uses organic solvents to

selectively extract the contaminants. This process may need to be repeated several times to extract the contaminant to a certain concentration level. The solvent itself can be treated and recycled. Supercritical fluid extraction uses a highly compressed gas (e.g., carbon dioxide) above its critical temperature to perform the extraction. This highly compressed gaseous fluid can be especially useful in removing contaminants from interstitial spaces of the matrix [1,30]. Supercritical CO₂ extraction is presented in a separate section. Solvent extraction technology potentially can be used for treatment of pesticides from waste groups WG02, WG03, and WG04 [29,30,31].

Process Description

This process achieves volume reduction by concentrating the pesticide into an extract phase. Solvent extraction typically consists of three types of subsystems:

- feedstock preparation
- extraction
- residuals treatment/solvent recovery.

As with soil washing, solvent extraction feedstock preparation typically includes excavation, followed by screening operations to segregate the soil by size into highly contaminated fines and minimally contaminated coarser soil fractions. This initial volume reduction can reduce the amount of soil that must be extracted, reducing the overall treatment cost. Some commercially available units treat the entire soil mass without initial volume reduction. If the soil is very wet (e.g., >70 percent moisture content), a dewatering unit is used to remove excess moisture before the extraction process [20,27,29,31,32,33].

During the soil extraction process, pesticide-contaminated soil is mixed with an appropriate solvent in a tank-based continuous countercurrent extraction. The extraction process may require several passes to reduce the solid-phase pesticide contamination to the desired level. After extraction, the solvent extract is pumped to a sedimentation tank for removal of soil fines [20,27,29,31,32].

A suitable solvent should:

- have high selectivity for the contaminant(s)
- have high saturation solubility for the contaminant(s)
- be immiscible in the feed material
- be stable
- be nonreactive and noninterfering with other soil-matrix components
- have favorable density, viscosity and interstitial tension properties
- have a sufficiently different boiling point from the contaminant(s) to allow post-treatment separation [29,34,35].

Residuals treatment subsystems include unit operations for air emission control, decontamination of the extraction solvent to allow solvent recycle and removal of residual solvent from the treated soil [20,27,29,31,32,33].

Data Needs for Technology Implementation

Data needs and possible effects for this technology are presented in Table 11.

Performance

The Sanivan Group developed the Extraksol™ solvent extraction process which was used to treat PCP-contaminated soil for the purpose of system development and demonstration of capabilities. A proprietary solvent was used in the 1-ton-per-hour pilot-scale unit. The process efficiency, presented in Table 12, was greater than 90 percent and greater than 99.7 percent, respectively, in two tests conducted on contaminated porous gravel. In addition, low post-treatment PCP concentrations were achieved (<0.82 mg/kg and <0.21 mg/kg). In a test on PCP-contaminated porous stones, the removal efficiency was lower, at 50 percent [32].

A bench-scale study using the B.E.S.T.™ process marketed by Resource Conservation Company (RCC) demonstrated a 99 percent removal efficiency for a number of pesticides in waste groups WG02 and WG03. Data from this

study is presented in Table 13. Data from other bench-scale tests using this process indicate chlordane removal efficiencies greater than 99 percent [1].

Process Residuals

Residuals include oversize materials, spent solvent, gaseous solvent emissions and treated soil. Oversize soil fractions can be returned to the site as backfill if sufficiently clean. To improve process economics, the solvent extract is generally recovered and recycled back to the extraction process. The mode of solvent recovery depends on the physical and chemical properties of the extract (solvent and contaminant). For pesticide extraction operations, distillation or evaporation can be used to recover a volatile solvent from the less volatile contaminant. In some cases, a second extraction with an aqueous solution may be the method of primary solvent recovery.

The extracted soil may need treatment to remove excess residual solvent. Dewatering (e.g., centrifugation), air or steam stripping, vacuum extraction, or biological treatment can be used to remove residual solvent from the soil. Gaseous emissions from system operations must be treated before release [20,27,29,31,32,33].

Table 11. Data Needs for Solvent Extraction. [36]

Data Needs	Possible Effects
Complexity of waste mixture	Affects solvent selection
Particle size	Oversize particles may require size reduction pretreatment
pH	Must be in a range compatible with extracting solvent
Contaminant size	Affects solvent selection and process efficiency; solvent extraction is least effective for very high molecular weight and very hydrophilic organics
Temperature	May impact solubility of contaminants in extraction solvent – this affects extraction efficiency
Metals	Strong reaction may occur during treatment process because of caustic additions
Organically bound metals	May be extracted along with organic pollutants and cause disposal/recycling difficulties
Detergents/emulsifiers	May retain organic contaminants and reduce effectiveness of process; may cause foaming, which hinders settling and separation characteristics
Soil permeability	Affects solvent-contaminant contact; low permeability soils may require additional contact time for effective treatment
Solvent characteristics	May impact treatment process if nonbiodegradable, toxic, or nonvolatile
Solvent extraction capacity	Affects mass of contaminant that can be solubilized in the solvent
Soil moisture content	Affects solvent-contaminant contact; soils containing more than 30 percent moisture may need to be dewatered before treatment

Table 12. PCP Removal Obtained in 1 Ton/Hour Extraksol™ Pilot-Scale Solvent Extraction Unit. [32]

Type of Waste	Type of Solvent ^a	Initial PCP Conc. (mg/kg)	Final PCP Conc. (mg/kg)	Removal (%)
porous gravel	#2	8.2	<0.82	>90
porous gravel	#2	81.4	<0.21	>99.7
porous gravel	#2	38.5	19.5	50

^aproprietary

Table 13. Pesticide Removal in Bench-Scale Study Using B.E.S.T.TM Solvent Extraction Process. [37]

Analyte	Feedstock (ppm)	Product Solids (ppm)	Removal Efficiency (%)
p,p'-DDT	500	0.2	99.96
p,p'-DDE	84	0.5	99.40
p,p'-DDD	190	0.05	99.97
Endosulfan-I	250	<0.02	>99.99
Endosulfan-II	140	<0.02	>99.99
Endrin	140	0.02	99.99
Dieldrin	37	<0.02	>99.95
Toxaphene	2,600	0.9	99.97
BHC-Beta	<30	<0.13	—
BHC-Gamma (Lindane)	<30	<0.07	—
Pentachlorophenol	150	1.9	98.7

Supercritical CO₂ Extraction

Supercritical CO₂ (SCO₂) extraction is a type of solvent extraction that exploits some unique properties of supercritical fluids. Many gases, including CO₂, exhibit enhanced solvent properties when compressed at conditions above their critical temperature (the temperature above which the gas cannot exist in the liquid state, regardless of pressure). Supercritical carbon dioxide forms when CO₂ is heated and compressed above 31°C and 1078 psi. In the supercritical state, the CO₂ is not a liquid, although it exhibits liquid-like densities and displays much better solubilizing properties and mass transport characteristics than subcritical, gaseous CO₂. Because the supercritical fluid remains in the gaseous state, it can penetrate spaces within contaminated soil much more readily than liquid solvents [29,30]. Several other gases such as ethylene, ethane, propane and dichlorodifluoromethanol (Solvent-12) have been tested in addition to CO₂ for treatment applications of supercritical fluid extractions[29].

Process Description

SCO₂ extraction systems consist of an extraction vessel that can be operated at elevated temperatures and pressure. Carbon dioxide from a liquified bulk supply is piped to a storage vessel where it is compressed to the desired operating pressure. The pressurized CO₂ is then heated to the system operating temperature and piped to the extraction vessel containing the contaminated soil. After the extraction process, contaminated supercritical CO₂ is piped to a separation vessel, where the pressure is rapidly reduced, causing SCO₂ to undergo phase transformation to gaseous subcritical CO₂. At lower temperatures and pres-

sure, the dissolved organic contaminants precipitate in the bottom of the separation vessel. Uncontaminated, gaseous CO₂ is piped to the storage vessel for recycling, while the extracted organics are collected for disposal [29,30].

Data Needs for Technology Implementation

Data needs for supercritical CO₂ extraction are presented in Table 14.

Performance

Supercritical fluid extraction processes have been used extensively in various applications such as decaffeinating coffee and extracting cholesterol from eggs, drugs from plants, and nicotine from tobacco [6]. The full-scale application of supercritical fluid extraction to the remediation of contaminated soils is in its infancy. Bench-scale SCO₂ studies on pesticide-contaminated soil suggest that full-scale implementations will be successful [6,38]. A pilot-scale supercritical fluid system that successfully remediated PCB-contaminated sediment using a mixture of propane and butane as the extracting solvent was demonstrated by CF Systems Corporation under the SITE Program [39].

The efficiency and choice of operating conditions of SCO₂ extraction systems for performing pesticide-contaminated site soil remediations will most likely depend on the specific contaminants present. Several sets of conditions (e.g., temperature and pressure combinations) may be needed to extract soils contaminated with more than one pesticide [6,29,30,38].

Table 14. Data Needs for Supercritical CO₂ Extraction [6,29,38]

Data Needs	Possible Effects
Complexity of waste mixture	Affects temperature and pressure combinations required for effective treatment
Contaminant polarity	Extractive efficiency of polar pesticides may increase with the addition of an enhancer, such as methanol or acetone
Soil permeability	Affects solvent-contaminant contact; low permeability soils may require additional contact time for effective treatment

Process Residuals

Residuals include treated soils, recyclable CO₂ gas, and liquid- or solid-phase pesticide contaminants. Decontaminated soils can be backfilled on site. The recondensed, separated pesticide contaminants can be stabilized and disposed of in a RCRA-permitted landfill. The CO₂ gas can be recycled to the extraction process [6,29,30,38].

Comparison of Option Costs, Advantages and Limitations

Costs

Figure 1 presents the cost ranges for the technologies discussed in this document; Table 15 lists critical factors affecting the cost ranges for the technologies discussed. Other remedial alternatives discussed in the primary reference document, Contaminants and Remedial Options at Pesticide Sites, are included for comparison. This information should be used as a guide only. Specific cost estimates should be generated for each site based on specific needs and circumstances. These costs include capital operations and maintenance (O&M) costs.

Advantages and Limitations

Tables 16 and 17 present generalized advantages and limitations, respectively, of the treatment technologies discussed. Other remedial options discussed in the primary reference are included for comparison purposes. Limita-

tions specific to a technology or site application are not addressed.

EPA Contact

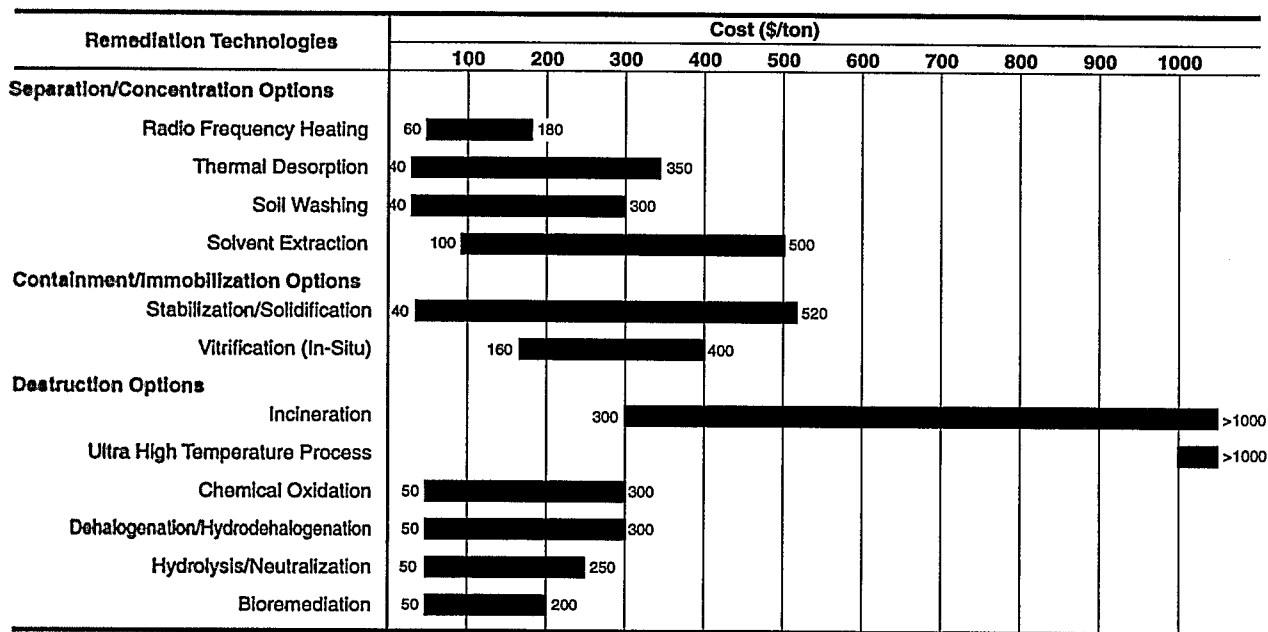
Technology-specific questions regarding remedial options at pesticide sites may be directed to:

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*No cost estimates for supercritical CO₂ extraction are available

^bIncineration and vitrification costs are per cubic yard

^cCost estimates were obtained from the references provided and through contact with technology vendors

Figure 1. Available Estimated Cost Ranges for Pesticide-Contaminated Soil Remediation Technologies^{a,b,c}. [1,40,41]

Table 15. Factors Affecting Cost Ranges for Technology Alternatives for Remediating Pesticide-Contaminated Soil.

Cost Factors	Remedial Technology											
	Radio Frequency Heating	Thermal Desorption	Soil Washing	Supercritical CO ₂ Extraction	Stabilization/Solidification	Ultra High Temperature Incineration	Hydrolysis/Neutralization	Chemical Oxidation	Bioremediation	Hydrothermal Oxidation	Chemical Oxidation	Bioremediation
Disposal	●	●	●	●	●	●	●	●	●	●	●	●
Vapor passage capabilities	●	●	●	●	●	●	●	●	●	●	●	●
Moisture content	●	●	●	●	●	●	●	●	●	●	●	●
Metals content	●	●	●	●	●	●	●	●	●	●	●	●
Volatile organic compounds content	●	●	●	●	●	●	●	●	●	●	●	●
Residuals/off gases requiring treatment	●	●	●	●	●	●	●	●	●	●	●	●
Energy usage	●	●	●	●	●	●	●	●	●	●	●	●
Pretreatment operations	●	●	●	●	●	●	●	●	●	●	●	●
PCB/dioxin concentration	●	●	●	●	●	●	●	●	●	●	●	●
pH	●	●	●	●	●	●	●	●	●	●	●	●
Clay, silt, humic content	●	●	●	●	●	●	●	●	●	●	●	●
Number and types of contaminants	●	●	●	●	●	●	●	●	●	●	●	●
Chlorinated organics concentration	●	●	●	●	●	●	●	●	●	●	●	●
Particle size	●	●	●	●	●	●	●	●	●	●	●	●
Treatment temperature	●	●	●	●	●	●	●	●	●	●	●	●

● technology for which cost incurred increased because of this factor

Table 16. Advantages for Technology Alternatives for Remediating Pesticide-Contaminated Soil.

Advantages	Remedial Technology											
	Radio Frequency Heating	Thermal Desorption	Soil Washing	Supercritical CO ₂ Extraction	Stabilization/Solidification	Ultra High Temperature Incineration	Hydrolysis/Neutralization	Chemical Oxidation	Bioremediation	Hydrothermal Oxidation	Chemical Oxidation	Bioremediation
Proven ability to reduce high concentrations to clean-up goals	●	●	●	●	●	●	●	●	●	●	●	●
Destroys or detoxifies pesticides	●	●	●	●	●	●	●	●	●	●	●	●
Can be implemented in-situ	●	●	●	●	●	●	●	●	●	●	●	●
Concentrates pesticides, reducing disposal costs	●	●	●	●	●	●	●	●	●	●	●	●
Effective on some inorganic co-contaminants	●	●	●	●	●	●	●	●	●	●	●	●

● technology for which a specific advantage is applicable

Table 17. Limitations for Technology Alternatives for Remediating Pesticide-Contaminated Soil.

Limitations	Remedial Technology											
	Radio Frequency Heating	Thermal Desorption	Soil Washing	Supercritical CO ₂ Extraction	Stabilization/Solidification	Ultra High Temperature Incineration	Hydrolysis/Neutralization	Chemical Oxidation	Bioremediation	Hydrothermal Oxidation	Chemical Oxidation	Bioremediation
High moisture content adversely affects treatment	●	●	●	●	●	●	●	●	●	●	●	●
Pesticides must be destroyed by another process	●	●	●	●	●	●	●	●	●	●	●	●
Produces residuals/off gases requiring treatment and/or disposal	●	●	●	●	●	●	●	●	●	●	●	●
Sensitive to median particle size, pH and/or media characteristics	●	●	●	●	●	●	●	●	●	●	●	●
Sensitive to co-contaminants	●	●	●	●	●	●	●	●	●	●	●	●

● technology for which a specific limitation is applicable

REFERENCES

- USEPA. 1994. Contaminants and Remedial Options at Pesticide Sites. EPA Contract No. 68-03-3482. Risk Reduction Engineering Laboratory, Washington D.C., Office of Research and Development, Cincinnati, OH, EPA 540/R-94/202.
- Federal Insecticide, Fungicide, and Rodenticide Act, Public Law 92-516.
- USEPA. 1988. Pesticides in Ground Water Data Base: 1988 Interim Report. Environmental Fate & Ground Water Branch, Environmental Fate & Effects Division, Office of Pesticide Programs, EPA 540-09-89-036.
- USEPA. 1991. FATE: The Environmental Fate Constants Information System Database. Environmental Research Laboratory, Office of Research and Development, Athens, GA.
- USEPA. 1990. National Survey of Pesticides in Drinking Water Wells. EPA 570-9-90-015.
- Hunter, G.B. January 1992. Extraction of Pesticides from Contaminated Soils Using Supercritical Carbon Dioxide. In Proceedings of International Workshop on Research in Pesticide Treatment/Disposal/Waste Minimization, T.D. Ferguson, Editor. EPA/600/9-91/047.
- Dev, Harsh and Tom Bajzek. Hydrocarbon Removal by In Situ Heating of Soil by Electrical Energy. ITT Research Institute, Chicago, IL.
- Dev, Harsh, Guggilam Sresty, and Paul Carpenter. In Situ Soil Decontamination by Radio Frequency Heating. ITT Research Institute, Tyndall Air Force Base, FL.
- U.S. Army. November 1992. Rocky Mountain Arsenal In Situ Radio Frequency Heating/Vapor Extraction Pilot Test Report, Volume I. Document Control No. 5300-01-12-AAFP. Rocky Mountain Arsenal, Commerce City, CO.
- USEPA. 1991. Engineering Bulletin: Thermal Desorption Treatment. EPA-540-2-91-008. Office of Emergency and Remedial Response, Washington D.C., Office of Research and Development, Cincinnati, OH.
- USEPA. July 1995. Applications Analysis Report: Low Temperature Thermal Aeration (LTTA) Process,

- Canonle Environmental Services, Inc. EPA/540/AR-93/504. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Washington, D.C.
12. Roy F. Weston, Inc./REAC and Foster Wheeler Enviresponse, Inc. 1993. EPA Contract No. 68-03-3482 and 68-C9-0033. Contaminants and Remedial Options at Solvent-Contaminated Sites. Roy F. Weston, Inc., REAC, Edison, NJ.
13. USEPA. 1989. Guide for Conducting Treatability Studies under CERCLA: Interim Final. EPA-540-2-89-058. Office of Emergency and Remedial Response, Washington D.C., Office of Research and Development, Cincinnati, OH.
14. USEPA. 1994. Technology Applications Report: Low Temperature Thermal Aeration (LTTA) Process, Canonle Environmental Services, Inc. EPA/540/A5-93/504. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
15. T H Agriculture & Nutrition Company, Inc. 1992. Use of Thermal Desorption for Treatment Pesticide Contaminated Soils. Report submitted to U.S. Environmental Protection Agency, Region IV, Atlanta, GA.
16. Dennis, R.M., D. Dworkin, and W.L. Lowe. 1991. Evaluation of Commercially Available Soil Washing Processes for Site Remediation. Proceedings from Hazardous Material Control/Superfund 1991, pp. 333-343.
17. Goldberg, E. 1995. German Washing Process Pulls Out Contaminants in a Fine Slurry. Soil and Groundwater Cleanup, August/September, pp. 34-37.
18. Sachse, J.D., A.J. Dietrich, D.H. Weigle, C.P. Keegan, D.C. Grant, and E.J. Lahoda. 1994. Mobile Soil Washing System. Atomwirtschaft Atomtechnik, Vol. 39, No. 3, pp. 199-201.
19. Bleber, D. and K. Crabtree. 1994. Washing Unit Churns through Diesel. Soils, November, pp. 14-17.
20. USEPA. June 1993. Applications Analysis Report: Resources Conservation Company B.E.S.T.TM Solvent Extraction Technology. EPA/540/AR-92/079. Office of Solid Waste and Emergency Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
21. USEPA. 1990. Engineering Bulletin: Soil Washing Treatment. EPA-540-2-90-017. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
22. USEPA. 1988. Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA-540-2-88-004. Office of Solid Waste and Emergency Response, Washington D.C.
23. USEPA. September 1994. Innovative Treatment Technologies: Annual Status Report, Sixth Edition. EPA 542-R-94-0005. Office of Solid Waste and Emergency Response, Washington, D.C.
24. URS Consultants, Inc., and Hazra Environmental Services, Inc. 1992. Pilot-Scale Soil Washing Study, Sand Creek Superfund Site, Commerce City, CO. Report to EPA Regions VI, VII, and VIII.
25. Frederick, R.M. and S. Krishnamurthy. 1994. Soil Washing Treatability Tests for Pesticide-Contaminated Soil. Remediation/Autumn, Vol. 4, No. 4, pp. 443-453.
26. Bechtel Environmental, Inc. 1990. "Feasibility Study for the FMC Fresno Plant Superfund Site." Report to MC Corp., San Francisco, CA.
27. USEPA. November 1989. Innovative Technology: BESTTM Solvent Extraction Process. Publication No. 9200.5-253FS. Office of Solid Waste and Emergency Response, Washington, D.C.
28. Conklin, A. 1995. Secrets of Clay: Why is it the Most Stubborn and Difficult Soil Type to Treat? Soil and Groundwater Cleanup, August/September, pp. 38-41.
29. Berkowitz, J.B. 1989. Solvent Extraction. In Standard Handbook of Hazardous Waste Treatment and Disposal, H.M. Freeman, editor, McGraw-Hill Book Company, NY, pp. 6.77-6.90.
30. DOE. August 1993. Technical Area Status Report for Chemical/Physical Treatment, Vol. II: Supercritical Fluid Extraction. DOE/MWIP-8. U.S. Department of Energy, Office of Technology Development, Washington, D.C., pp. L-2.1-2.7.
31. DOE. August 1993. Technical Area Status Report for Chemical/Physical Treatment, Vol. II: Conventional Solvent Extraction. DOE/MWIP-8. U.S. Department of Energy, Office of Technology Development, Washington, D.C., pp. L-1.1-1.8.
32. Paquin, J. and D. Mourato. 1989. Soil Decontamination with ExtraksolTM. Paper presented at the 3rd International Conference on New Frontiers for Hazardous Waste Management, Pittsburgh, PA, October 10-13.
33. USEPA. February 1995. SITE Technology Capsule: Terra-Kleen Solvent Extraction Technology. EPA540/R-94/521a. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
34. USEPA. January 1990. Project Summary: Cleaning Excavated Soil Using Extraction Agents: A State-of-the-Art Review. EPA/600/52-89/034. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
35. Khodacloost, A., P., J.A. Wagner, M.T. Suidan, and S.I. Safferman. Solvent Washing of PCP Contaminated Soils with Anaerobic Treatment of Wash Fluids. Water Environment Research, Vol. 66, No. 5, pp. 692-697.
36. USEPA. 1990. Engineering Bulletin: Solvent Extraction Treatment. EPA-540-2-90-013. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.

37. D.A. Austin. 1988. The B.E.S.T. Process – An Innovative and Demonstrated Process for Treating Hazardous Sludges and Contaminated Soils. Presented at 81st Annual Meeting of APCA, preprint 88-68.7, Dallas, TX.
38. Dooley, K.M., R. Gambrell, and F.C. Knopf. 1988. Supercritical Fluid Extraction and Catalytic Oxidation of Toxic Organics from Soils. In Proceedings of the Thirteenth Annual Research Symposium, Office of Research and Development, Cincinnati, OH.
39. USEPA. August 1990. Applications Analysis Report: CF Systems Organic Extraction Process, New Bedford Harbor, MA. EPA/540/A5-90/002. Office of Emergency and Remedial Response, Washington, D.C., Office of Research and Development, Cincinnati, OH.
40. USEPA. January 1993. Selected Alternative and Innovative Treatment Technologies for Corrective Action and Site Remediation. EPA/542/B-93/001.
41. USEPA. September 1994. Innovative Treatment Technologies: Annual Status Report, Sixth Edition. Office of Solid Waste and Emergency Response. EPA 542-R-94-005.

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